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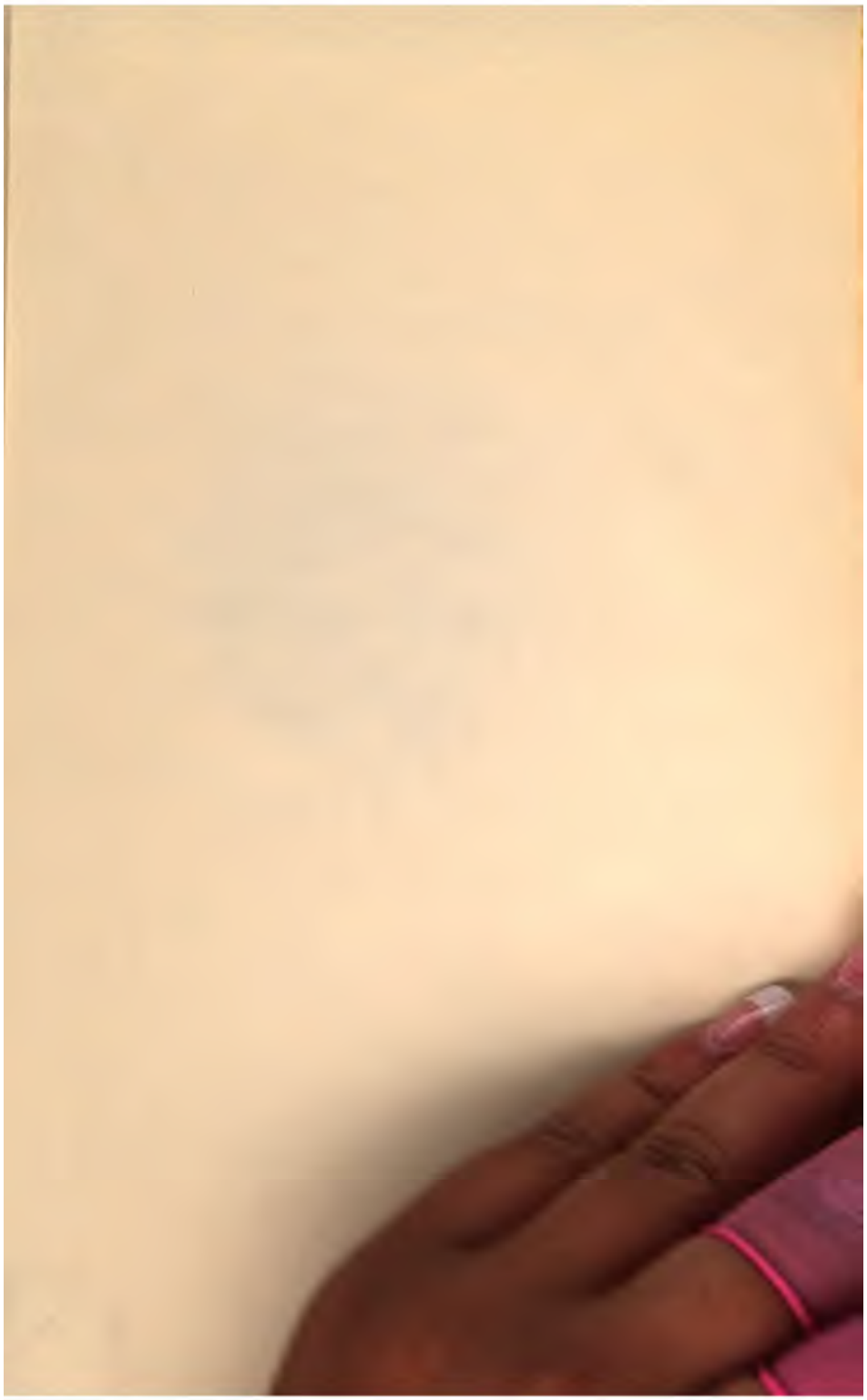

SYNCHRONOUS SIGNALLING IN NAVIGATION

BY

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PREFACE

THIS little book is written in the hope that it may assist in promoting a reform in our system of maritime signalling. The subject is important from many points of view. It is no exaggeration to say that a scientific system of signalling, such as is herein advocated, would, if successfully carried into effect, beneficially influence our commercial prosperity. This it would do not only by promoting faster sea traffic, but by generally diminishing maritime risk. It must, indeed, necessarily affect an insular community like ours in many far-reaching ways. Increased speed and safety mean closer colonial and international ties, augmented passenger traffic, the saving of life, etc., etc.

It may be asked by some how far synchronised signalling is practically available and how far it is only theoretically possible. The question

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should be answered, and I shall endeavour to do so as briefly as possible.

Synchronised signalling is based on a fact, the ascertainment of which is old in the history of scientific advance: that disturbances travel with different speeds in different media. Light and other electro-magnetic disturbances (such as telegraphy or "wireless") may be regarded as instantaneously propagated; sound travels relatively slowly; and in water more than four times as fast as in air. These are fundamental facts which have been made the subject of accurate measurements and certainly require no further experiments to establish. They are the scientific bases of synchronous signalling. The practical basis differs somewhat according as we consider its application to coastal stations, or to the prevention of collision. Regarding the first, we may say that two factors only are involved: (1) The possibility of simultaneously originating at a signal station any two or all three of these disturbances; and (2) the possibility of hearing and timing them on board ship.

No one acquainted with what has been already accomplished would hesitate in considering both these conditions as perfectly feasible. Fortunately we may take even a stronger position. The method has been made the subject of a practical trial by the Hydrographic Department of the United States Navy. All three kinds of signals—wireless, submarine, and aërial—were sent out synchronously from the Nantucket Shoals Lightship. A suitably equipped vessel, receiving signals both by chronograph and stop-watch, made a cruise in hazy weather in the neighbourhood; at intervals finding her distance from the lightship by timing the arrival of the signals. The results are shown on a chart dated 1911. The known course of the vessel and the course as defined by the signals appear as three lines which show a quite satisfactory agreement over conditions of distance varying from one to eight nautical miles.

In short, my answer to the question, so far as it applies to coastal signalling, is that practical realisation of the method must be regarded

as only waiting upon such experiments as are needed to determine among the various modes of application which are best suited to stations of varying importance and to vessels of varying size. In this direction a reform appears to be undoubtedly practicable which must at once have far-reaching beneficial consequences, and which can be put into effect at a cost of time and money trifling compared with the interests involved.

The application of synchronous signalling to the even more important problem of avoiding collision involves some modification of these statements and some additional considerations. The value of the method depends to a considerable degree on the universality with which it is taken into use. The ship which is unprovided with the protective system becomes to some extent a hindrance to those who possess it. She can neither announce herself scientifically to other ships nor can she avail herself of their announcements. Accordingly such a vessel, if permitted to sail in waters suited to the use of synchronous

signalling, becomes a check on the freedom of the fully equipped vessel.

Again, modifications of the existing Board of Trade rules respecting collision at sea are required to legalise and standardise the new method. For these reasons, official trial of the method is most desirable. If the sanction of successful trial were attached to it, no compulsion would be requisite in order to ensure its adoption. Ship-owners in their own interests would not hesitate to face an outlay which would probably be small, in order to render their property not only more secure but more lucrative. Official trial is, therefore, specially important in this case.

Finally, the method of avoiding collision involves the use of a new instrument. But I do not think that any one who has considered the nature of the Collision Predictor can possibly anticipate trouble with it.

I must add a word on a subject of minor importance. My own ideas on synchronous signalling have been evolved at comparatively recent date, and I have pursued them in

ignorance of the existence of any previous suggestions in the same direction. In point of fact, the problem of finding the distance from the shore, by timing the arrival of simultaneously started signals in different media, appears in certain patents—as I am informed on good authority—dating back to a period before wireless and submarine signalling were accomplished facts. That is to say, to a period before the practical realisation of the idea was possible. In my obliviousness of these suggestions I was not alone. For some reason very complete obscurity seems to have enveloped the matter. Enquiries made by me some months ago in usually well informed quarters and among high authorities gave no clue to the early ideas, much less to the experimental work accomplished at the other side of the Atlantic. The latter fact has only quite lately reached me through the courtesy of the Submarine Signal Company.

Since the appearance of three papers by me on this subject in the Proceedings of the Royal Society, I have received some kind and

helpful criticism. To Professor H. C. Plummer, Royal Astronomer for Ireland, Mr. J. T. Jackson and Mr. Horace H. Poole my acknowledgments are especially due. I have endeavoured to profit by this criticism while still keeping the treatment of the subject in its simplest form. I assume a minimum of knowledge on the part of the reader. The subject is worthy of a fuller and more technical book, but the time for that has not yet come. This one is purely introductory.*

Trinity College, Dublin.
March, 1916.

* A forthcoming paper on the subject, by Professor Plummer, in the Proceedings of the Royal Society may with advantage be consulted.

SYNCHRONOUS SIGNALLING IN NAVIGATION

In 1827 Colladon and Sturm carried out an experiment on the velocity of sound in water. The details are familiar to students of physics. Two boats were moored at known distance apart in the Lake of Geneva. A submerged bell was supported from one boat, and a hearing trumpet was immersed in the water at the other boat. The hammer which struck the bell was mechanically connected with an arrangement for igniting a charge of gunpowder in a position visible from the other boat. The stroke of the hammer and the flash of the powder were simultaneous. At the further boat the observer noted the interval elapsing between the appearance of the flash and the sound of the bell as this was transmitted through the water. The velocity of the propagation of

light is so great that this interval is the time taken for the sound to travel through the water.

A very little consideration of what is involved in the experiment of Colladon and Sturm reveals its applicability to the important problem of enabling a ship to find her distance from the shore, or from another vessel, in fog or thick weather, or in darkness. For it is evident that if Colladon and Sturm had started with a knowledge of the velocity of sound in water, the distance separating the boats could have been determined from the interval required for the sound to traverse the distance. We make, indeed, familiar application of the principle involved when we estimate the distance of the lightning flash by counting the number of seconds intervening between the appearance of the flash and the sound of the thunder, allowing 1,100 feet to each second.

Similarly, if a signal station on the shore sends out two simultaneously emitted signals—one, say, in air, the other, say, in water—which travel outwards at different velocities, a ship

off the coast receiving these signals can determine her distance from the station by noting the interval or lag between the arrivals of the faster moving signal and the slower moving signal, and for every second or fraction of a second allowing the appropriate distance of travel. Nothing can be simpler.

The method involves necessarily the emission of signals propagated with different velocities. We may avail ourselves of air signals which travel at about 330 metres (1,100 feet) per second; of submarine sound signals which travel at about 1,400 metres (4,700 feet) per second; of wireless and light signals which are propagated practically instantaneously. We possess three different combinations. If we use air and water sound-signals the lag of the slower upon the faster is 4·3 seconds to the nautical mile (6,000 feet). That is to say, at a distance of one mile from the signal station, the sounds which have been simultaneously emitted, become displaced by this time interval. Using air sounds and wireless (or light flash) signals the lag is 5·5 seconds to the mile.

Finally, using wireless or light-flash signals along with sound in water the lag is 1·2 seconds to the mile. The maximum sensitivity is obtained by combining aërial with etherial signals.

The leading advantage of using the combination of wireless and submarine signals is the certainty of hearing the sounds in all conditions of the atmosphere. It is well known that, during fog, sound signals occasionally become mute over a certain area which is, normally, well within the limits of audibility. It cannot be said to be a frequent phenomenon. According to the present writer's experience it is possible to put in many years of cruising in all sorts of weather conditions without meeting with it. But every now and again, although rarely, cases are reported to the Lighthouse Boards and complaints made to the effect that such and such a signal has not been heard. The trouble being quite outside the power of the signal operator to modify or control.

There is another consideration arising out of this phenomenon. It is believed that refraction of the acoustic wave is the cause of it.

Now, if the wave is deflected, the path of the sound will not be direct even when it is heard; and there may be nothing to suggest to the listener that it is not direct. Hence the distance determinations might be in some degree falsified. Observation alone can definitely determine whether the error involved can become serious. There is reason to believe that it would not be serious. Fog-producing conditions seem generally to extend to only a small height. Fogs are often limited to heights of less than 100 feet. If in such cases the refraction is upwards, the sound then travelling approximately horizontally and reaching the listener from above, the increase of distance in a shallow fog bank may be relatively small. However, as already stated, nothing can be definitely inferred till observations are made: observations which are best carried out by the methods we are now discussing.

According to the proposed method of synchronised signalling the mariner approaching land in fog or thick weather determines his distance from the signal station—which may

be lighthouse, lightship or buoy, by noting the interval in seconds between certain signals reaching his ship. The determinations may be effected on the chronograph; which, on this new system, would become an important adjunct to navigation. Although electric registration would allow of observers being located in any part of the ship, there is a considerable advantage in the one observer receiving and recording all the signals—wireless, submarine, aërial, or luminous. There is no practical difficulty in arranging for all these signals to be received upon the bridge. And if one officer attends to this duty, not only is the error involved in "personal equation" diminished, as we shall see, but the benefit of experience and special training is obtained.

We refer now to the more important vessels. A chronograph is an easily understood and an easily operated instrument. Its use has the merit of keeping a record, if desired, of the observations; and, what is more important, it renders the observations more accurate. It is, of course, easy to graduate its readings

directly to distance according to the different available combinations of signals. No calculations would then be required. The lesser ship may be content with the use of the stop-watch. Nothing else is needed for the safe navigation of the vessel. The distance between the receipt of the signals is timed just as we time the interval between the arrival of the competitors in a race. The dial of the watch may, however, read to distances and carry scales to suit the different combinations of signals. No intelligent man can go wrong; and after some practice, which may be obtained in fair weather at any time, the power of reading with sufficient accuracy will be acquired.

Readings of this kind may certainly be relied upon to half seconds. With crisp sounds and a very little practice the degree of accuracy would even amount to the customary minor interval used in timing racing events—one-fifth of a second. However, taking the half second, we have an accuracy in the determination of distance of about 700 feet when we compare aërial and submarine sounds; of

less than 550 feet when we compare wireless (or luminous) signals with aërial sounds, and an accuracy of 2,350 feet when submarine signals are used with the instantaneously propagated etherial signals. The latter combination is, evidently, the least sensitive, but even in this case the distance should be determined with care to less than one quarter mile.

It is important to note that the degree of accuracy attainable in the readings is enhanced by the fact that the errors of "personal equation" must be all of the one sign and hence tend to cancel in the successive observations which go to each determination. The observer necessarily in every case first hears the signal and then makes the record. The delay (which constitutes the personal equation) between the receipt of the signal and the making of the record, tends to be the same for the receipt of the fast and the slow moving signal. But it is the *difference* in time between the record of the one and the other which matters. Hence the error is more or less eliminated.

But a system of signalling suggests itself

which does away with the necessity of all time-measuring instruments, and which, if not capable of the same degree of accuracy as attends the use of the chronograph or stop-watch, will yet afford quite sufficient accuracy to ensure the safety of the ship.

The system referred to involves sending out the faster of the two signals at such accurately timed intervals as will allow them to take the place of the time-measuring instrument on board ship. What may be called group signalling is resorted to. Suppose, for instance, thirty successive repetitions of the faster signals —be they wireless or submarine—are emitted, timed to intervals of one second : and the slower travelling signal—aërial or submarine—is sent out synchronously with the first of the thirty fast-moving signals. The mariner at sea notes that the slow-travelling signal reaches him, not along with the first of the successive fast-moving signals, but along with, let us suppose, the sixth of these signals—or near to it. The lag is, in fact, nearly five seconds. Now, if he is dealing with wireless and aërial signals this

tells him that he is just a little less than a mile from the station. The observation is easily made and its indication is certain unless there is something abnormal in the propagation of the aërial sound. If he is dealing with wireless and submarine signals he must be much further away: about four miles or a little more.

In this system it is, of course, necessary to group the faster signals so that the sailor knows with which of the faster signals the slower signal is synchronised. Thus after thirty of the faster signals there would be a pause, say, of another thirty seconds, and then the first of a new group of signals, and with this first signal the slower signal is emitted. In this way mistakes are rendered impossible. The mariner waits for the first signal of each group; counts "one" for it; then he counts "two" for the second signal, and so on till the slow signal comes in. His count gives him the lag at once. The signals themselves tell him the distance. In every respect this system commends itself. It is not detrimental to accuracy, for, of course, the chronograph or stop-watch

may be applied to the measurements if desired. It affords an easy method of characterising the signal station. We may vary the number of strokes in a group or the length of the pauses so as to avoid the possibility of neighbouring stations being confused.

With synchronised invisible signals there is a good deal to be said in favour of uniting visible ones. Where, in a lighthouse or lightship, a flash system is already in operation, it may be justly urged that submarine and aërial signals will gain in value by being synchronised with the flash. It is true, of course, that in thick fog the flash may not be seen; but there are conditions other than those of fog when a sailor would be glad to know his distance from the shore. In this case he can do so even if his ship possesses neither wireless nor submarine installation. He does it exactly as the distance of the lightning flash is determined.

Finally, a system of buoyage is probably possible for more local usage; a system which would enable the principles we are discussing to be applied to local needs. A buoy which,

when rocking, rings a bell carried some height above the sea is a familiar and useful aid to navigation. The energy available in these buoys is considerable, and it should be feasible to operate a submarine bell-stroke synchronously with the aërial stroke. The buoy in this case at once becomes a distance indicator when any swell or sea exists to rock it. Or, again, a light shown by the buoy may be caused to flash synchronously with the bell strokes, and in this way an indicator of distance is obtained which would be serviceable to the smallest vessel provided with no special fittings.

Of course many practical considerations arise with respect to the best forms of sound-producing apparatus. The sounds emitted must be crisp and loud. The wail of the syren will not do. For the purpose of synchronisation the further quality of control of the instant of starting or stopping must be secured. An abrupt beginning or ending renders a signal available for distance determination. A variety of aerial sound-producers are already in use which may be applied to synchronised

signalling. Explosive signals have advantages in carrying power, and the ease with which electric ignition, securing a practically instantaneous signal, can be applied. Distance tends to blur the crispness of sounds, but I have found that gunfire can be timed to less than half a second even at a distance of eight or nine miles—a degree of accuracy unnecessary at distances so great. When explosive signals are used an allowance has to be made for a somewhat greater velocity of transmission. This applies both to explosions in air and in water. For submarine signalling, however, it is doubtful if the submarine bell can be much improved upon. It may be operated electrically, and may be heard at from six to fifteen miles from the station. This apparatus has been developed to a high state of mechanical perfection, and may be described as ready for immediate application to synchronised signalling. The strokes may be timed to any desired frequency, and forms suitable for attachment to ships are available. As regards electro-magnetic signals—whether "wireless"

or luminous—control of the moment of emission may, of course, be had. In the case of wireless the carrying power of the ship's installation is generally unnecessarily great. Short range signals are desirable.

The conversion of existing installations to the purpose of synchronised signalling cannot be described as a general problem, although certain considerations as regards the most economical methods will doubtless generally apply. Electric and pneumatic control are both available where direct mechanical connections are inconvenient. The solution of the problem will, in many cases, probably, involve the installation of a simple clockwork distributor of current from a storage battery—the latter being already part of the equipment of the station. The timing is, in this case, effected in the simplest manner, and is entirely adjustable, the mechanism of a good clock constituting the greater part of the requirements.

To the mariner this system gives not only his distance from the signal station. It also gives him his position on the chart. In the

most extreme case we may assume that his compass course and speed are all that is known to him when first he picks up the distance-signal. He then recognises from the character of the signal the name of the signal station. He is able to locate it on the chart and he knows that he is, say, five miles from it. But he may evidently be anywhere upon a circle of five miles radius having the station as centre. This may be literally true, for the signals may come from a lightship. How is he to find his place upon the circle? He can evidently do this if he can determine the bearing of the signal station from his ship. We assume that the seeming direction of the sound is not reliable, and, of course, that he can see no light signal. In this case the sailor draws a line on a piece of paper representing his own course. He puts a mark on the line representing his position when he heard the signal, and from this point he describes a circle to the radius of five miles or whatever the distance was. He now awaits another signal. When it comes he gets a new distance—say four miles—and he makes a

second mark on the line at a distance from the first mark corresponding to his run in the interval between the signals, and, always to the same scale of distance, he strikes from this second point a circle to the radius four miles. This circle in general intersects the first circle at two points. The signal station is at one or other of these two points; for his observations have given him two circles upon which the signal station must be located, and these are the only points common to the two circles. Now, in nine cases out of ten the problem is completely solved by this information. But there are cases when he is still undecided as to which point marks the position of the station. When this is so, he alters his course towards one of the points till he picks up the next signal. This tells him finally; for, if he finds he has got nearer to the signal station by the amount of his run, the particular one of the points he is heading for must be the correct point; if the new distance shows him a less advance than this, the other must be the point whence the signals come. Lastly, he takes

the bearing of this point with reference to his own course, i.e., with his last position as laid down on the paper; and knowing now the bearing of the station from his ship and the distance of the station he can lay down his position on the chart.

Other cases arise which we need not discuss. One may be referred to. On thickly-inhabitated coasts the sailor will occasionally hear the distance signals of two stations. This at once gives him his position; for he knows his distance from two points on the coast, and the point of intersection of two arcs, struck to these distances as radii, locates his vessel.

The methods we have now considered must be regarded as making an addition to the functions of signal stations; an addition which converts them from being merely directional—and often deficiently directional—to being contributory to the solution of that most important of problems, the determination of the ship's position. To this end all the methods and principles of navigation and nautical astronomy are directed; an end which acquires its highest

importance when land is approached. But, hitherto, when sights of the coast were not available, to soundings alone could the mariner turn for help, when the safety of his ship required the determination of his position on the chart. And without decrying the assistance often derived from that time-honoured method it must be admitted that too often the nature of the bottom and the depth are uncertain and even deceptive guides.

But when the signals themselves can be so ordered as to tell the sailor how far he is from the coast, in the thickest darkness and fog he can advance with confidence. For each instant he feels his way and can mark his progress upon the chart. He feels his way by signals which tell him of his approach mile by mile to the lighthouse which may be invisible to him and, again, of its recession as he goes on his way; till some new signal leads him yet further on his course. Those who have passed a night of rain, wind and impenetrable darkness, hearing signals whose location was uncertain, or have tried to make harbour

by guesswork as to the distance and bearing of the lightship whose gun is heard at intervals, will alone fully appreciate the security involved in a knowledge of distance from the land.

Avoiding Collision

The danger of collision threatens the mariner everywhere upon his voyage. But the principles we have considered above may be applied to avert the risk under many conditions; more especially in open sea and in the less crowded waters. In such areas the danger of collision is, in a sense, greater than in heavy traffic; for, owing to the considerable distances involved, speed is often maintained and the risk taken.

The vessels are supposed to be provided with the usual wireless, and with a crisp and loud sound-signalling apparatus. Submarine receiving and transmitting apparatus can be fitted to any ship, is already carried by some, and in the future will doubtless be carried by many. Its use for the present purpose would be considerable, under conditions when

any doubt existed as to the transmission of aerial sound signals.

Upon the appearance of fog or thick weather and on dark nights it would be incumbent upon every ship under way to emit certain wireless signals—of short range—at intervals. For instance, it might, be necessary for a ship to issue such signals every two or three miles of her course. The wireless signals she issues are intended to announce her presence. They may be replaced by or accompanied by the usual aërial sound signals and by submarine signals if desired. Or, again, this advertising signal may be a synchronised distance-signal. It would, obviously, be advantageous to confer upon it such a character as would distinguish it from any other signal.

When two ships emitting these signals at intervals become aware each of the other's presence they commence the systematic emission of synchronised signals. We shall assume these signals timed to intervals of two minutes. Let us imagine ourselves on board one of the ships—which we shall call A. We know from

the first distance-signal we pick up that a ship—B—is at a distance, say, of 4 knots. We at once signal our course and speed, and presently get an answering signal giving the course and speed of B. We do not require to know any further particulars about her. It is a regulation that if either A or B alters course or speed she must at once signal that fact. In our hypothetical case we assume that our own ship is holding a course due south at a speed of 16½ knots and that B tells us that her course is N.E.¾E. and her speed 11 knots.

We now take into use the instrument depicted in the accompanying figure. It consists of a circle upon which compass bearings and angles are engraved. It carries two limbs, *a* and *b*, which rotate independently about the centre and which can be clamped in any position. An arm, *c*, is pivoted upon a sliding piece or cursor, which can be slipped along the limb *b*. This arm carries centrally a transparent divided scale, as shown. With the help of this instrument we proceed to determine whether we are

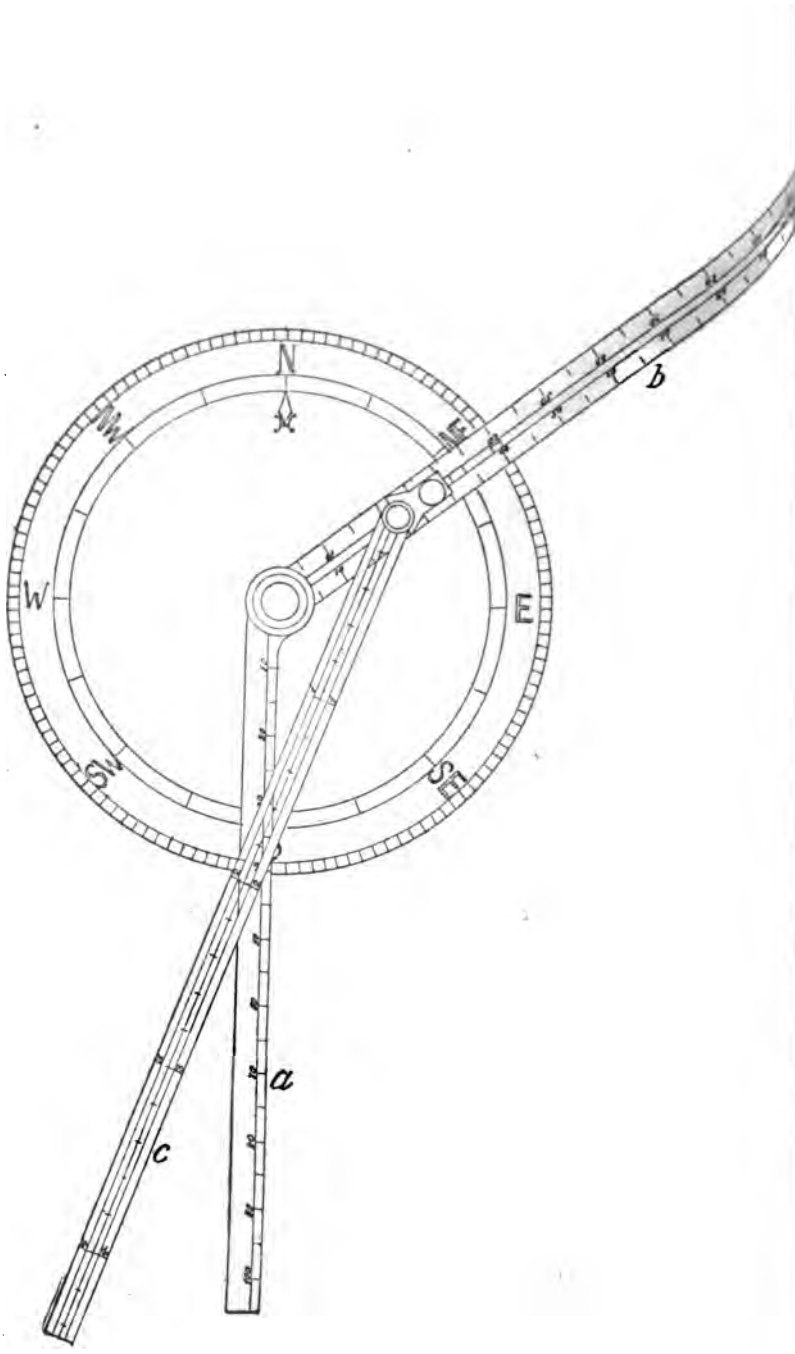

FIG. 1.

threatened with collision with the vessel B or whether she will pass clear.

We first set the limb *b* to the course N.E.¼E. held by B, and the limb *a* to the course S held by A. Then we slide the cursor along the limb *b* till it reads 11 of the scale divisions into which it is divided; and we then inflect the arm *c* across the limb *a* so that the centre line of the scale on *c* cuts the scale on *a* at a reading of 16½ divisions. (It is to be noted that the smaller subdivisions are not shown in the figure, and that the readings actually given upon it are those for the next signal; as will presently appear.)

We now take note of the fact that the distance of B from A is 4 knots. We lay this off, mentally, on the arm *c*. That is, we note that the number 4 upon it is the distance of the ship B from A. If desired, there may be a marker sliding along *c* to mark this reading; which is the initial distance separating the vessels. Looking at the instrument at this stage we will find that the limb *a* intersects the arm *c* at a reading of 0·8 knot. This tells us that the ships are

nearing each other at the rate of 0·8 knot every two minutes. And we are thereby informed of the fact that if there is to be collision it will occur in ten minutes from the moment we received the first signal. We get the ten minutes by dividing 0·8 into 4—that is, into the distance first separating the ships—and multiplying the quotient by 2. For five times the distance 0·8 knot is contained in the original 4 knots, and it takes two minutes to traverse each of them. But we do not yet know whether there is going to be collision or not.

We cannot determine this vitally important point till we get the second signal. After the lapse of two minutes we get this signal. If this shows that 3·2 knots now separate the vessels collision is threatened. If the new distance is something different—say, 3·4 knots —it is not threatened; the ships are going to pass clear of one another. Observe that 3·2 added to 0·8 amounts to the initial distance of 4 knots.

However, before we finally decide, we receive the third signal. But meanwhile, if we wish

to avoid arithmetic, we may shift the cursor along the arm *c* till it stands at 22: that is, we shift it another 11 knots representing the advance of the ship B in the second two minutes. We need not touch the arm *c*. It moves parallel to itself and takes up the correct position corresponding to the run of A during the second two minutes. We see, in fact, that it reads 33 on the limb *a*, and that the arm *c* is cut at 1·6 knots. The figure of the Collision Predictor —as we may call the instrument—shows these readings approximately. When at length the third signal arrives we know that if the first reading is to be confirmed and there is really risk of collision, it must show the new distance to be 2·4 knots. In short, *collision is indicated when the distance signalled as still to run added to the distance already covered by the approaching vessels is equal to the original distance.* If now the second reading of distance is 2·4 knots we may be sure of the danger; and, also, as four minutes have now elapsed we know there are but six minutes left before collision is imminent.

It is of course open to us to check the result

still further and take a third or even a fourth reading. There will be time after we have taken this reading to put the ordinary rules of the road into force. And here we are assisted by the fact that *the compass direction assumed by the arm c on the dial of the Predictor gives us the bearing of the other ship if collision is threatened.*

Although it takes some time in the telling, the actions of the navigator are of the simplest kind. This is essential to the utility of an instrument which may have to be used, conceivably, under circumstances of anxiety and hurry. For although with proper vigilance there should be ample time for carrying out the observations, yet some error or negligence on either ship may render quick decisions imperative. Now, after the first setting of the Predictor, the mariner has practically accomplished all that is requisite to enable him to judge if the succeeding signals indicate danger or safety. Let us consider the successive steps. The first advertising wireless of the other ship is recognised by its distinctive character from

all other wireless signals. It is answered, and the signals giving course and speed are sent out from each ship. The synchronous signals follow. If the ships are within a certain distance of each other—say 4 or 5 knots—these are heard. The navigator on A, when first he hears the signals of B, sets the Predictor according to the courses and speeds of the two ships. This is done in a few seconds. When, after the lapse of the regulation time—we assume two minutes—the second signal comes in, he is already in a position to say whether there is danger threatening him or whether there is not. And the navigator on B is in the same position.

For, so soon as the navigator sets the Predictor to the courses and speeds of the two ships, the reading on the arm *c* gives him what the travel of the ships towards each other will be in two minutes *supposing there is danger threatening him.* In the example taken above, for instance, he finds that if there is going to be collision the ships must be advancing towards one another at the rate of 0·8 knot in two

minutes. He knows, then, when the second distance-signal reaches him, that if this shows the original distance shortened by 0·8 knot there is risk of collision. In short, in two minutes after receiving the first synchronous signal he is able to state with tolerable certainty—in most cases with absolute certainty—whether there is danger or not. The uncertain cases are those where the 0·8 knot is *approximately* indicated. Thus, if he gets 0·7 knot (i.e. the distance to run is read as 3·3 knots) he is justified in concluding that the ships will probably pass clear. But this result may be due to error. If there is departure from the 0·8 knot in the other direction this indicates error without any doubt, as will presently be seen. Our point here is that, in all cases of wide clearance of ship and ship, the mariner is informed of his safety in two minutes after the receipt of the first distance-signal, and in cases of "close shave," or conditions approximating thereto, two or four minutes more must settle all doubts.

Using, as in the above example, figures read-

ing to 0·1 knot, I assume the use of the combination wireless and aërial sounds or submarine and aërial sounds. The degree of accuracy attainable in distinguishing safety from danger depends, of course, on the sensitiveness of the distance determinations. Using wireless and submarine 0·2 knot should be determinable. Before considering the matter further it is necessary to understand the principles involved in these results.

The theory of the Collision Predictor is simple enough. In the adjoining diagram we suppose A, sailing due south, has started at the point 0 and will reach the positions 1, 2, 3, etc. in successive intervals of two minutes. B is at the distance d_0 when A is at 0. If a circle is struck with 0 as centre and d_0 as radius, B must, then, be somewhere on this circle. B is moving in a N.E.$\frac{3}{4}$E. direction. We lay off the course of B from 0 accordingly, and along the line 0 B we lay out points corresponding to the travel of B in successive intervals of two minutes. This gives the points 1′, 2′, 3′, etc.

Now, if keeping the distance d_0 as radius

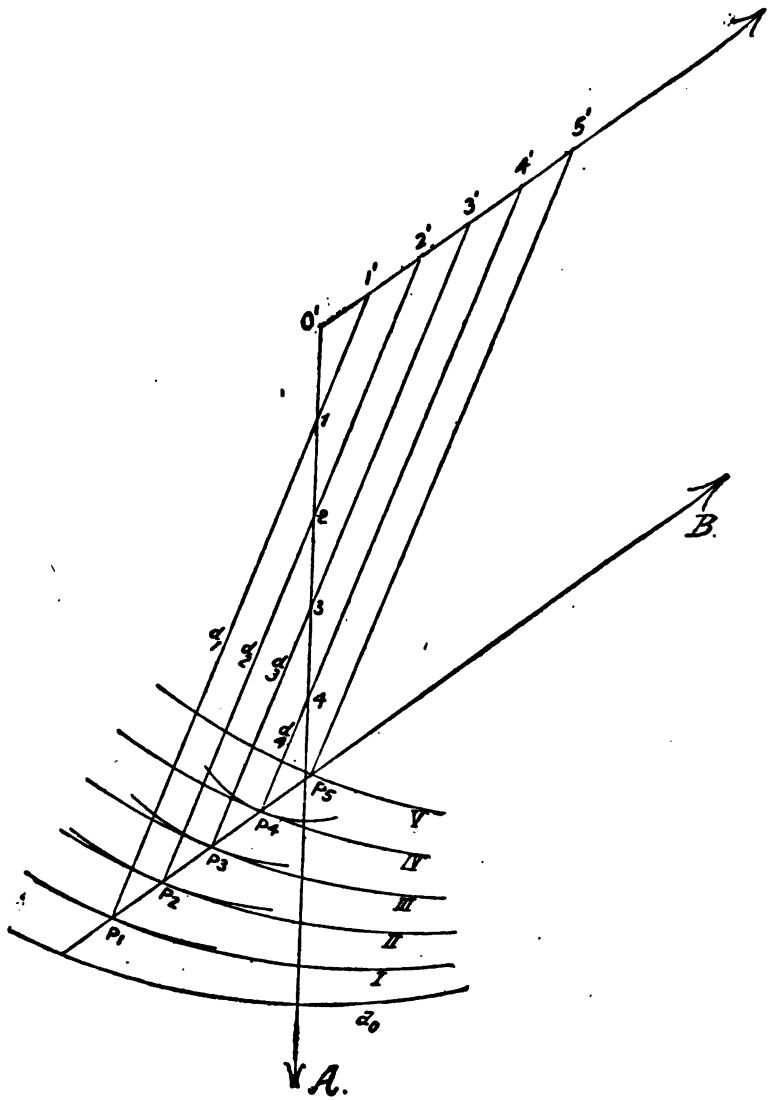

FIG. 2.

we strike circles from the points 1′, 2′, 3′, etc., the ship B must be transferred from one of these circles to the next every two minutes. In the figure we have shown only portions of these circles; marking them I, II, III, etc.

When the second signal comes to A, A is at 1 and B is somewhere on circle I. The distance is now d_1. With 1 as centre we describe a circle to this radius. B must be on this circle, and as we know that she is also on circle I she can only be at one or other of the points of intersection of these circles. Or, if the circles do not intersect but touch on a point of tangency, she must be at that point. We can at this stage predict risk of collision or safety. If the circles intersect there is safety. If they merely touch, there is going to be collision. Before proceeding we can see in a general way the truth of this deduction. For if B may be at either of two points and all the conditions of course and speed be satisfied there cannot be collision. There cannot be two possible lines leading to collision. Collision can only

occur if both ships are making for a common point, and as two parallel lines cannot pass through the one point the two possible N.E.$\frac{3}{4}$E. lines for the path of B cannot conform to the conditions of collision. But, on the other hand, if there is a point of tangency upon which B is necessarily located, the path of B is obviously unique and must lie along the N.E.$\frac{3}{4}$E. line through that point. This is the criterion of collision. The line leading to collision is necessarily unique for each vessel.

The diagram is drawn to show the conditions of collision. The point P_1 is the point of tangency. B must be at that point when the second signal is sent out. And the line P_1 B through it, directed N.E.$\frac{3}{4}$E., must be her path. There will be collision when her progress along this path brings her to the line upon which A is advancing going due south.

The point P_1 is the meeting point of two circles, the centre of one being at 1 and the centre of the other being at 1′. Now it is a fact that a line joining the centres of tangent circles passes through the point of tangency.

Hence, the line 1 1′ passes through P_1 if produced; or is *in directum* with 1 P_1. Similarly, if when A is at 2 we strike from this point the circle to radius d_2 we evidently get the line 2′ P_2; and so also for the successive positions of the two ships. Now, the equality of these successive lines is easily proved. Hence we have the successive intercepts 1 1′, 2 2′, 3 3′, etc. added to the successive distances d_1, d_2, d_3, etc. equal to the original distance d_0. And this fact is just what we read on the arm *c* of the Collision Predictor.

But we see that this is only true when the circles meet on points of tangency. If the circles to radius d_1, d_2, etc. cut the circles I, II, etc., the successive distances separating the vessels must be greater than those of the diagram. In fact the diagram gives the condition when the successive distances are the least possible for the courses and speeds; in other words, the condition when the rate of approach of the two ships is the maximum for the courses and speeds. And this again is a criterion of collision. To some this will be quite obvious.

When two ships are advancing so as to collide their rate of mutual approach must be the maximum for the courses and speeds. Both ships are then directed towards a common point, and all their speed is bringing them directly to that point. Hence their rate of approach is the maximum. Again, we may say that *if the rate of approach is not the maximum there is not going to be collision; and the effect of the deficiency will add up every moment.* Each successive determination of distance will show a greater and greater departure from the distances shown in the diagram and marked d_1, d_2, d_3, etc.

The Collision Predictor, we see from all this, determines the relative speed of the two vessels. The first setting of the limbs *a* and *b* to the compass directions and the adjustment of the arm *c* according to the run of each ship in two minutes, afford at once the rate at which the ships are approaching each other *if collision is threatened.* In the example taken this rate is 0·8 knot in two minutes. If this rate is departed from we know there is not going to be collision. And we tell whether it is departed

from or not by noting on two successive distance determinations if the run in two minutes has been 0·8 knot or some other distance.

This is rigorously true supposing there was perfection in all the measurements. But some error there may be. First we may state at once that a reading greater than what is indicated on the arm *c* *must* involve error. Only error can make the rate of approach of the ships towards one another appear to be greater than what it is if collision is threatened. For instance, in the example, if, after the first distance-reading of 4 knots, we get in two minutes a distance-reading of 3·1 knots we know there is error. For this reading involves a rate of approach of 0·9 knot in two minutes. Whereas the reading on the arm *c* tells us it will be 0·8 knot if collision is threatened; and this is the maximum rate. Hence there is error somewhere. Such a reading as this points to collision, for we know that there is certainly error at least to the amount of 0·1 knot in the reading, and that but for this error the danger reading might be obtained. But there might be error the other

way. The distance-determination might give 0·7 knot when it should give 0·8 knot; again referring to the example. Now, how are we to distinguish this reading from safety? Safety readings must give us less than 0·8 knot as the rate of approach of the vessels in two minutes, and how do we know that this is not such a reading? The answer is that the succeeding readings will tell us. If there is true safety the equation *distance already run* + *distance still to run* = *original distance* will be more and more departed from at every reading. For the ships are approaching each other at a rate less than that maximum rate which is proper to collision, and the lesser rate of approach involves a continual increase of the distance between them over what would prevail if the maximum rate of approach obtained. This steady departure from the distances given by the Predictor is the criterion of safety, and, if we read aërial sound signals against wireless, and our determinations are even no closer than to one half second, a fairly near passing of the other ship would be distinguishable from colli-

sion. But, of course, the mariner would never take risks. Practice would soon give him the reliable limits of the means at his disposal, and he puts into force the rules of the road if his readings approach these limits. If aërial sounds are for any reason not trusted and the observations are made with submarine sounds against wireless, the loss of accuracy is considerable. It is true that the carrying power of submarine signals seems to be very considerable, and a greater number of signals would be available. Loss of accuracy means needless deviations but not necessarily increase of risk. The difficulty of distinguishing between threatened collision and the near passage of the other ship increases with the loss of sensitiveness.

It remains to define, so far as this can at present be attempted, the conditions under which the use of synchronised signals may be advantageously adopted for the prevention of collision at sea. In crowded waters their use might be attended with risk of confusion. As already indicated, it is not suggested, that in such waters the method would supersede

slow speeds and the usual sound signals as at present enjoined on mariners. The real advantage of the method must be found in more open waters where the distances are sufficiently great to tempt the navigator into the maintenance of high speeds, although there must be a certain risk of collision. But the presence of more than two vessels in the same area need not and should not create confusion. To appreciate this we must imagine ourselves again upon our ship A. Now, the other ships are not first heard simultaneously. B is first heard and it is determined after, say two signals, that we are safe from B. In coming to this decision we do not require to keep the Collision Predictor occupied with B. After the first setting of the instrument upon a knowledge of courses and speeds we may, of course, write down what all the subsequent distance-determinations respecting B would show if collision is threatened. Accordingly if C is heard shortly after B we can turn our attention to her and deal with her in the same manner. We must remember that the process of feeling their way and watching

their risks is going on aboard all the other ships. Each ship's Commander knows what his own risk is, and he knows also that he must only alter his course so far as safety requires; and he can form a fair estimate of what amount of change in course and speed may be made without endangering the calculations of the other vessels. There should be no difficulty in framing rules which would meet all cases likely to arise.

And even a more general claim might, perhaps, be put forward for the use of synchronised signals among ships and for the use of the Collision Predictor. They confer upon the sailor a power of feeling his way in fog or darkness which, in some respects, would actually render him more secure than he would be in clear daylight without their help. For he knows his distance from the other vessel, and he knows what is coming, and if there is risk he can tell *when* the danger threatens; information which vision alone will not give him. The use of the Predictor will not, probably, be confined to fog or to the darkness of night. It may be of service in the full light of day. In this latter

case the sailor can even predict collision without synchronous signals. For if the Predictor is set to the courses and speeds, collision is threatened in one case only—if the bearing of the other ship is observed to be that shown by the inclination of the arm *c* on the compass dial of the instrument.*

* This use of the Predictor is further considered in the Appendix.

It may be well to explain that the Predictor, as shown in the figure p. 34, is graduated for distance signals sent out every two minutes: the scale on the arm *c* being 30 times as open as the knots-per-hour scale on the limbs *a* and *b*. To render it available for signals spaced at intervals of, say, one minute—and there is much to be said in favour of the shorter interval—the ratio of the scales needs only to be adjusted accordingly; that is, made as 60 to 1. Interchangeable scales might easily be provided.

APPENDIX

Sources of Error.—It may very naturally be asked if under conditions of storm the velocity of signals transmitted through the air may not be seriously interfered with. The answer is that the velocity of sound in air is so great compared with the velocity which the air itself can attain in a gale that the error is but small. A wind blowing at forty miles per hour is moving at about 60 feet per second. Now the velocity of sound in air is about 1,100 feet per second. If the wind is blowing against the direction in which the sound is travelling to the mariner the time for the transmission of the sound is increased; the advance of the sound wave being retarded 60 feet each second. Thus its actual velocity becomes 1,040 feet per second. The sailor would consequently hear the sound later than he would if the air was still, and he might conclude that he was further

from the signal station than he actually was. But we see that he is only 60 feet out for every second of time by which the signals are relatively displaced. And this is true whether he is judging his distance by comparison of aerial and submarine signals or aërial and wireless. In the latter case the displacement of the signals is, as we have seen, 5·5 seconds at a distance of a nautical mile. In a forty-mile gale, therefore, he would misjudge his distance —over-estimating it—by 330 feet. On the other hand, if the wind was blowing from the signal station to him he would receive the sound signal sooner than in still air, and he would estimate the signal station as 330 feet closer than it actually was. If the wind blows in any direction transversely to the direction in which the sound travels to him the error must be less. It is evident that an error of 330 feet in the knot is not important. Moreover, it is easy to make an allowance for it which would be sufficiently accurate to render the effect quite negligible.

There is also a small error arising from

abnormal conditions of atmospheric temperature. Between 0°C. and 15°C. the velocity has been found to increase about 3 per cent. We may take it that the velocity increases 2 feet per second for each rise of 1 degree centigrade. The error is evidently negligible, for over the range of 15 degrees the error would be only 180 feet in the nautical mile. And again, in this case, an approximate allowance is easily made.

An important matter—which investigation alone can clear up—is the question as to whether the acoustic vagaries which are occasionally observed during time of fog seriously affect the velocity of aërial sounds. As already remarked, there is evidence of acoustic refraction under certain conditions. I am not aware of this evidence ever having been observed in open sea. Such instances as have come to my notice have been near land. In any case the amount by which the path of the wave is distorted is probably not great. The reasons for this statement are the limited and very local character of the soundless areas which indicate the

refraction and the known shallow depths of fog-banks. In the case of ships under way and changing their position, an error affecting the determination of distance arising from this source would very certainly be quite local; and it is improbable that it would prove a source of danger when a succession of signals were received during the approach of two vessels. Reliance on aërial sound signals between vessels under way would seem to be perfectly justified. After all, such signals have been in use for many decades as the sole resource of the mariner under the adverse conditions. This alone proves that the phenomenon of inaudibility which is the sole evidence for refraction must be rare indeed in open water. Our conclusions on this matter chiefly affect the efficiency of synchronous signalling as applied to avoiding collision. It is desirable in this case that distances should be read as closely as possible. The reason is largely one of convenience and economy. The frequency with which the rules of the road must be put in force become greater the less sensitive the

determinations of distance. This is obvious. A sensitive appreciation of distance will tell the sailor with perfect certainty that his ship will pass clear, when the less sensitive reading compels him to alter his course.

Finding the Alternative Bearings of the Other Vessel.—In describing the Collision Predictor it was stated that if collision is not going to occur we can determine from the simple geometrical construction, whereby we investigate the principles involved in the Predictor, two alternative paths for the ship B.

Although the mariner as a rule is only interested in the ascertainment of his freedom from risk of collision or otherwise, yet cases may arise in which the determination of the alternative bearings of the other ship may be of importance to him. The following is the means by which this information is obtained.

We shall assume (Fig. 3) that A is heading due north and that B is going S.E. We suppose A to be at the point 0 when first she hears from B. And we assume the speed of A to be such that in two minutes she shifts her

position from 0 to 1. The points 2, 3, 4, etc. therefore represent her position at succeeding intervals of two minutes.

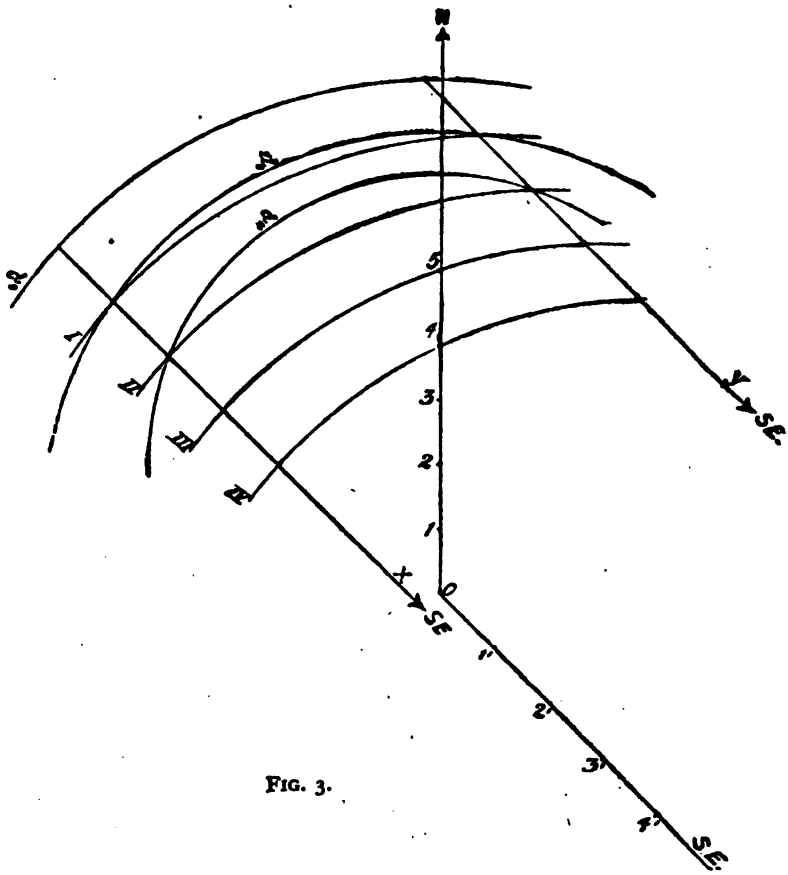

FIG. 3.

When at 0 she hears that B is at a distance of d_0 knots and learns the course and speed of B. The navigating officer on A then lays off a

line through 0 bearing S.E. and marks off on it the displacement of B in successive intervals of two minutes, i.e. the points 1′, 2′, 3′, etc. He takes in his pencil compass the distance d_0 and strikes the circles d_0, I, II, III, etc. from the successive points 1′, 2′, 3′, etc. At this stage all he knows regarding the position of B is that she is somewhere on the circle d_0 and that as she is being displaced in a S.E. direction by the distance 0–1′ every two minutes, she must be transferred from one ot these circles to the next in this interval of time.

When two minutes have elapsed the navigator on A receives the second distance-signal from B. This gives the distance d_1. If d_1 is less than d_0 the ship B must be approaching him and her position must be somewhere on the N.W. half of the circle I. Going to the point 1 and taking the distance d_1 in the compass he strikes a circle to this radius. It will intersect the circle I at two points which will lie on the N.W. half of circle I. B is at one or other of the points of intersection.

In the case illustrated in the figure it is assumed

that d_1 is less than d_0. If d_1 is greater than d_0 B is evidently receding from A and a circle struck from 1 with d_1 as radius gives the points of intersection in the S.E. half of the circle I. The reasoning in all cases is plain. We know that B is somewhere on the circle I and also that she is somewhere on the circle d_1. And as the points of intersection are the only points in common to the two circles, B must be at one or other of them.

As already pointed out, this is the case of safety. If there was risk of collision the circle d_1 would meet the circle I tangentially; giving one only point for the location of B. Or there might be errors sufficient to hide the tangency and give two approximating points of intersection. As stated above, the third distance signal will serve to distinguish such a spurious appearance of safety from true safety. For if there is a true intersection the next value d_2 will show a much greater departure from the condition of tangency. Thus we see in the figure that this second observation could not be mistaken for tangency. The reason is that if the ships are

not going to collide they are approaching one another more slowly than if they were going to collide, and the effect on the distance separating the vessels mounts up every instant.

The above construction is easily and rapidly made and gives the alternative positions of the other vessel. It is known on A that B is advancing along either of the lines tending S.E. as shown in the diagram.

If it is desired to ascertain the bearing of B from A this can, in general, only be done by A altering her course towards either of the lines in question. The ensuing signal tells A how far this has resulted in lessening or increasing the former rate of approach. This, of course, gives the required information. Doubtless there would be many cases when this procedure would not be required. If, for instance, the separation of the alternative paths is large and atmospheric conditions are believed to be normal so far as sound conveyance is concerned, then the apparent direction of sound signals from B, if this is the form of slow-moving signal she is using, will serve to distinguish between

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